A STUDY ON THERMOFORMING PROCESS OF STRETCHABLE CIRCUIT AND ITS PERFORMANCE IN MANUFACTURING OF AUTOMOTIVE LIGHTING

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by

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LIST OF ABBREVIATION

2-D	Two-dimensional
3-D	Three-dimensional
PC	Polycarbonate
PET	Polyethylene Terephthalate
T_g	Glass Transition Temperature
T_c	Crystalline Temperature
T_m	Melting Temperature
CNT	Carbon Nanotube
FEM	Finite Element Method
SEM	Scanning Electron Microscopy
DSC	Differential Scanning Calorimetry
PCB	Printed Circuit Board
LED	Light Emitting Diode
LDS	Laser Direct Structuring
MID	Moulded Interconnect Device
PTH	Plated-Through Hole
THT	Through-Hole Technology
THD	Through-Hole Device
SMT	Surface Mount Technology
SMD	Surface Mount Device
IML	In Mould Labelling
PDMS	Polydimethylsiloxane
PI	Polyimide

ACA	Anisotropic Conductive Adhesive
ICA	Isotropic Conductive Adhesive
QFP	Quad Flat Package
PBGA	Plastic Ball Grid Array
CAD	Computer Aided Design
ASR	Area Stretch Ratio
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
DMA	Dynamic Mechanical Analysis

KAJIAN MENGENAI PROSES PEMBENTUKAN TERMO LITAR BOLEH REGANG DAN PRESTASINYA DALAM PEMBUATAN LAMPU AUTOMOTIF

ABSTRAK

Litar tercetak telah berkembang bermula daripada papan litar tercetak ke litar fleksibel dan peranti acuan sambung (MID). Evolusi litar jenis-jenis ini adalah disebabkan oleh batasan dan permintaan yang tinggi terhadap reka bentuk litar kompleks bagi memenuhi kehendak pelanggan. Walau bagaimanapun, proses pembuatan MID memerlukan proses yang kompleks kerana melibatkan peralatan yang maju seperti mesin laser untuk menghasilkan litar tercetak di atas bahagian 3-D. Dalam kajian ini, proses pembuatan alternatif diperkenalkan untuk membina litar-litar berfungsi menggunakan dakwat boleh diregang yang dicetak pada substrat 2-D dan kemudian dijelmakan kepada bentuk 3-D melalui proses termopembentukan. Satu produk lampu bahagian belakang kereta kebangsaan dipilih sebagai produk rujukan. Acuan untuk proses pembentukan termo dibuat berdasarkan kaedah kejuruteraan terbalik yang mana dimensi bahagian lampu diukur menggunakan mesin pengukur koordinat (MPK) dan kemudian dipindahkan ke dalam lukisan 3-D menggunakan perisian Solidworks. Lukisan itu dibaca oleh mesin kawalan berangka berkomputer (KBC) melalui kod yang dihasilkan oleh pembuatan berbantu komputer (PBK) untuk menghasilkan acuan. Dakwat pada mulanya dicetak pada substrak termoplastik yang rata menggunakan teknik percetakan skrin. Dakwat tercetak dirawat di bawah 120°C selama 30 minit di dalam ketuhar untuk membentuk litar berkonduktif tinggi. Litar dengan substrat telah dijelmakan kepada bentuk 3-D melalui proses pembentukan

termo mengikut bentuk acuan yang direka serupa dengan reka bentuk lampu automotif sedia ada. Kemudian, diod pemancar cahaya (LED) dipasang pada litar dengan mendispenskan perekat konduktif pada sambungan LED dan dirawat sekali lagi pada 120^{o}C selama 10 minit untuk membentuk ikatan yang kuat pada sambungan LED. Prestasi mekanikal dan elektrik lampu automotif reka bentuk baru dicirikan dan dibandingkan dengan reka bentuk sedia ada menggunakan peralatan seperti meter pelbagai, probe empat titik, spektrometer, mikroskop elekron pengimbas (MEP) dan mesin ujian universal. Walaupun litar reka bentuk baru telah meregang dan berubah bentuk yang membawa kepada pertambahan rintangan litar, prestasi elektriknya menunjukkan hasil yang menjanjikan. Tidak terdapat perbezaan yang ketara antara reka bentuk baru dan reka bentuk sedia ada lampu automotif dari segi penggunaan kuasa oleh sistem dan fluks bercahaya LED. Proses pembuatan litar bercetak yang baru ini menawarkan kaedah alternatif masa depan dalam pembuatan produk lampu automotif.

A STUDY ON THERMOFORMING PROCESS OF STRETCHABLE CIRCUIT AND ITS PERFORMANCE IN MANUFACTURING OF AUTOMOTIVE LIGHTING

ABSTRACT

Printed circuits have been developed started from printed circuit board to flexible circuit and moulded interconnect devices (MID). The evolution of these kinds of circuit is due to limitation and highly demand of complex circuit design to fulfil the requirements of customers. However, manufacturing process of MID requires complex process since it involves advance equipment such as laser machine to produce printed circuit on 3-D part. In this research, an alternative manufacturing process was introduced to construct functional circuits using stretchable ink printed onto 2-D substrate and then transformed into 3-D shape by thermoforming process. A rear lighting product of national car was chosen as a reference product. Mould for the thermoforming process was fabricated based on reversed engineering technique where the lighting part dimensions were measured using coordinate measuring machine (CMM) and then transferred into 3-D drawing using Solidworks. The drawing was read computer numerical control (CNC) machine through coding generated by computer aided manufacturing (CAM) to manufacture the mould. The ink was initially printed on a flat thermoplastic substrate using screen printing technique. The printed ink was cured under 120^{o}C for 30 minutes in an oven to form a highly conductive circuit. The circuit with the substrate were transformed into 3-D shape through thermoforming process according to the shape of mould which was designed similar to the existing design of automotive lighting. Light emitting diode (LEDs) were then assembled on the circuit by dispensing conductive adhesive at the LEDs joints and cured again in the oven at 120^{o}C for 10 minutes to form strong bonding at the joints. Mechanical and electrical performances of the new design of automotive lighting were characterised and compared with the existing design using equipment such as multimeter, four point probes, spectrometer, scanning electron microscopy (SEM) and universal testing machine. Even the circuit of the new design had stretched and deformed that led to increase in circuit resistance, its electrical performance shows promising results. There was no significant difference between new design and existing design of automotive lightings in terms of power consumption by the system and luminous flux of LEDs. This new manufacturing process of printed circuit offers a future alternative method in manufacturing the automotive lighting product.

CHAPTER ONE

INTRODUCTION

1.1 Background

In early stage of development, conventional electronic circuits are fabricated on flat rigid boards with multiple copper patterns that interconnect the components using lead-free solder. These printed circuit boards (PCBs) offers an efficient and low cost for manufacturing process. However, there are demands to integrate electronics in 3D objects where the electronic circuits follow the surface shape of the object in order to reduce weight and material use, increase comfortability and more attractive design.

The use of LEDs in automotive lighting has become trend nowadays. The manufacturing of this LED lighting system for automotive requires certain process such as laser direct structuring (LDS) which allows 3D circuit printing. There are three primary steps included in LDS processes: (1) the polymer surface is modified by laser; (2) the laser modified specimen is activated through chemical activation; and (3) the activated specimen is plated using electroless deposition of copper (Islam et al., 2009). However, this manufacturing process is expensive and requires advance laser equipment. Since it is costly and has limitation on minimum conductive spacing of 0.3 mm for laser equipment capability, then continued efforts in research has to be done to come out an alternative process.

The advancement in materials research has contributed to introduction of stretchable materials which can be bended, stretched and twisted and it is useful for electronics field. This allows a stretchable paste printing process on polymeric substrate using surface mount technology knowledge and thermoforming process. The stretchable electronics technology has several advantages such as allowing increased circuit density and eliminates bulky connections and wiring. Also, its assemblies may be shaped and flexible during its use (Someya, 2013).

There are many applications of the stretchable electronic circuits that has been explored by researchers such as use in medical purpose where sensor devices can be integrated directly on human body as a patch or embedded in a wearable textile (Axisa et al., 2007; Matsuhisa et al., 2015; Van Den Brand et al., 2015). Its stretchability and flexibility could accommodate any shape even it is complex.

1.2 Problem Statement

Recently, the main automotive lighting part is manufactured using moulded interconnect devices (MID) technology. This technology involves complex process since it requires advance equipment such as laser machine to produce printed circuit on 3-D part.

As alternative to MID method, stretchable printed circuit is introduced using thermoforming process to manufacture automotive lighting. However, a complete technique has not been studied to accomplish the whole process. When dealing with the thermoforming process, there are several parameters that affect the final product properties. However, behaviour of printed circuit on thermoplastic substrate is not well studied so far and additional parameters are needed to be considered in order to achieve desired product properties. Also, the application of this technique in manufacturing of an automotive lighting product requires further testing on product performances under mechanical and electrical condition.

1.3 Objective

Objectives of this research are:

1. to suggest a product concept using stretchable material as printed conductor and thermoforming process for automotive lighting application,
2. to investigate the effect of thermoforming process of automotive lighting on electrical performance of the system, and
3. to characterize the mechanical performances of thermoforming product with respect to stretchable circuit.

1.4 Scope of Work

In this work, stretchable circuit is constructed by using commercial available conductive ink through screen printing technique. One selected stretchable conductive ink is used to form a functional circuit for automotive lighting. Mechanical testing such as pull test of LED joints and vibration test follow Japanese Industrial Standard (JIS Z 3198-6) and JEDEC Standard (JESD22-B103B) respectively. All the measurements and evaluations of the new design automotive lighting are compared to performances of an available automotive lighting product (Proton Saga FLX) as a benchmark. Finite element simulation of the thermoforming process is used to visualise the behaviour of the substrate in terms of area stretch ratio and thickness after deformation according to mould shape.

1.5 Thesis Organisation

There are five chapters in this thesis. In chapter one, a brief presentation of background study, problem statement, objectives and scope of research introduced. In chapter two, literature studies on types of circuits developed in electronic industry and detailed of stretchable circuit application are presented. Methodology approach in developing a new technique in manufacturing of automotive lighting has been highlighted in chapter three. In chapter four, effects of thermoforming process on stretchable circuit and thermoforming product performance are discussed in detail. Finally, conclusion and recommendations for future work is pointed out in chapter five.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Printed circuit design development starting from printed circuit board (PCB) to flexible circuit and then moulded interconnect device (MID) occurs due limitation of previous design and high demands towards a more complex design of circuit to accommodate the part shape in certain application. The latest circuit design tends to complement the previous circuit design in order to fulfil the requirements.

Currently, requirement for 3-D circuit in many industries such as automotive and telecommunication has encouraged further research in 3-D circuit. Advance in material has introduced stretchable ink to be used for printed circuit on thermoplastic substrate where thermoforming process is needed to transform the circuit from 2-D to 3-D. Consideration on substrate material, circuit printing technique and thermoforming parameters are necessary in order to apply stretchable circuit in the thermoforming process.

2.2 Evolution of Circuit Design

Circuit design started with printed circuit board (PCB) that replaced all mechanical wiring bonding. Then, flexible circuit was developed at which a part of the circuit board could be bent instead of all rigid body. Currently, moulded interconnect device (MID) had been implemented in automotive and telecommunication industries.

2.2.1 Printed Circuit Board (PCB)

PCB is s substrate of a paper or glass fabric impregnated with a resin, usually epoxy, phenolic or silicone (Brindley, 1990). There are two types of boards that typically used which are single-sided boards and double-sided boards. Single-sided boards are used when minimum cost is concerned but when the numbers of components or jumper wires are too many, double-sided boards are considered. It can be with or without plated-through hole (PTH). In order to choose which boards to be used, PCB area to component area ratio should be considered as follow:

Table 2.1: PCB to component area ratio (Leonida, 1989).

Board Type	**Single-sided**	**Double-sided PTH**
Discrete components (ICs not more than 5% of the area)	2-3	1.5-2
Mixed (ICs from 35% to 50%)	2.5-4	2-3
IC board (discrete components not more than 20%)	4-6	2-3

The electronic components are assembled on the circuit boards by two ways: through-hole technology (THT) using through-hole devices (THDs) and surface-mount technology (SMT) using surface-mount devices (SMDs) as illustrated in Figure 2.1.

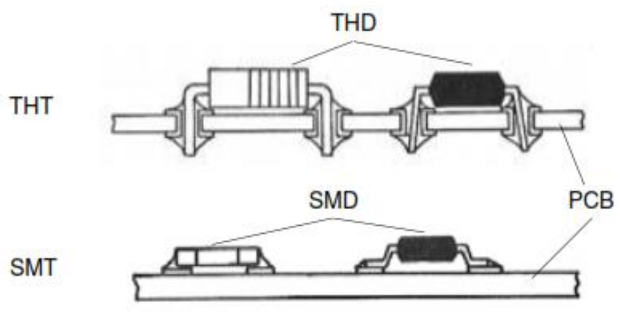

Figure 2.1: Assembly principles of THT and SMT (Coombs, 2008).